Virtual Verification of Automotive Steering Systems

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Abstract

The vehicle industry is in a transformation where software and electronics are revolutionizing the way we engineer the cars of the future. This is particularly true for steering systems, which have developed from passive mechanical systems to now enabling advanced driver support systems and the evolution toward fully autonomous driving. With this ever increasing complexity, relying only on physical testing is no longer practical due to slow feedback loops from testing back to development and the lack of repeatability. The question addressed in this paper is how computational methods can help to increase test coverage, shorten development cycles and enable continuous integration of software for steering systems. In particular the development, validation and application of methods to virtually release steering systems for passenger vehicles is presented.

1 Motivation

Demands on steering systems have steadily grown as cars have become faster and heavier and safety requirements have increased. In the past, these requirements primarily impacted mechanical and hydraulic systems, but in recent years an increasing emphasis is placed on electronics and software functionality [1].

As the rate of functional growth continues to increase, it is becoming necessary for more complex products to reach maturity earlier in development cycles [2]. In addition, testing that was previously possible only through subjective methods must be performed using objective criteria as time and prototypes become increasingly scarce [3]. Also repeatability of testing, required for regression testing, where the revisions of the software are re-tested and analysed for differences in results [4], is a challenge in physical prototypes.

In the current product development cycle, the road release presents a significant obstacle to addressing these challenges. This development step represents the conclusion from the engineering and testing departments that the product is mature enough to be operated in the field (for example on public roads) and currently necessitates subjective evaluation in a physical prototype. Thus the development of new methodologies for this application are critical to maintaining a competitive technical advantage.

To address these challenges, virtual methods are developed to enable testing of solutions before hardware is built and to find issues early – front-loading, as well as fully automatic, repeatable and safe testing of real driving situations. This paper will present how virtual methods have been developed specifically to address the road release of steering systems which is believed to be a critical step in enabling continued functional growth and innovation with steering system development in particular.

2 Organization

The use of vehicle simulation for a road release has mutual advantages for both vehicle manufacturers (OEM) and suppliers, and the development of these methodologies must be correspondingly collaborative. In addition to the rapidly evolving context of current and future automotive steering systems, this changes the typical division of work for a release.

2.1 Collaboration

By developing the model evaluation criteria and methodology together, the team is able to identify and address problems quickly, improving the quality of results using the shared expertise of a vehicle manufacturer and steering supplier. Key aspects of this teamwork are:

- Organizational buy-in and commitment from both sides.
- Agreed standard maneuver definitions (e.g. ISO standards) for validation of the virtual vehicle environment – proprietary test methods are not shared.
- A dedicated team with project managers from both vehicle manufacturer and supplier with the method development as a separate project outside the ordinary project work. Regular project meetings both face-to-face and online.
- Use of an existing vehicle for the method development and validation.

The division of responsibilities for the release itself remain as in the past, as shown in Figure 1. Rather than making a physical prototype available, an OEM provides the supplier with a virtual prototype and environment that is used in parallel or as a replacement to a traditional release. The supplier's process and release content remain its own.

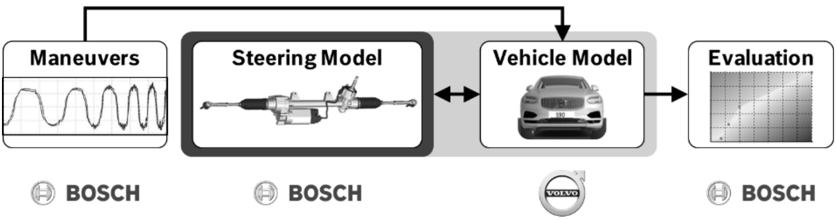


Figure 1: Breakdown of responsibilities with a release using virtual methods. As before, OEM remains responsible for vehicle-level content.

2.2 Prioritization

Although the release process remains the responsibility of the supplier, both the OEM and supplier can achieve benefits through the use of vehicle models for release activities A breakdown of typical product development cycle with respective priorities of team members is shown in Figure 2, where it is shown that the primary OEM benefit is in the early stages of the development when physical prototypes are scarce and expensive. For the system supplier, the primary benefit is during cyclical regression testing where short feedback loops and repetitive testing are required. All of these are key strengths of the virtual methods developed in this project.

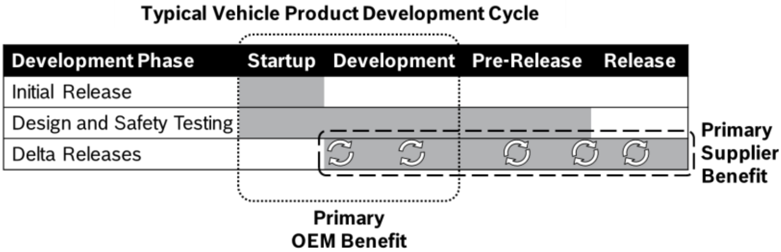


Figure 2: Breakdown of typical product development cycle with respective priorities of team members.

By focusing on implementing virtual methods in phases of the release where there is a common benefit, we can ensure that both parties achieve increased test coverage and shorter development cycles at the same time

3 Equipment

In order to achieve these goals efficiently, the method development should be organized appropriately by matching the product requirement being evaluated and the test equipment used.

3.1 Driving simulator

The Volvo Cars driving simulator, or DiM (Driver in Motion) platform, was developed to subjectively assess full vehicles and vehicle subsystems using virtual models instead of physical prototypes [5]. It consists of a full size cockpit, resting on a hexapod that is placed on a platform capable of planar motion. In total the cockpit has 9 degrees of freedom (full 2D-motion in the base platform of a hexapod and full 3D-motion of freedom between the top and base platform of the hexapod) which enables exceptional perception fidelity related to steering feedback in particular.

3.2 Steering system test bench

Steering system test benches offer physical testing of a complete steering gear and steering column. The construction is largely common between Volvo and Bosch:

- Two linear drives or hydraulic cylinders connected to the tie rods to represent the road loads. They can be force or position controlled.

- A steering robot capable of representing the driver either with torque or angle controller in open or closed loop control.

The inputs to the steering robot and tie rod actuators can be taken either from measurements in a physical vehicle, from full vehicle simulations (e.g. in Adams/Car or IPG CarMaker) or by having a vehicle model in the loop. Simple models can also be implemented in Simulink, for example if it is enough to represent the road forces with a spring load.

At the Robert Bosch Automotive Steering location in Schwäbisch Gmünd, there are a number of similar test benches developed in-house, however the System-HiL in particular offers advantages for virtual verification (see Figure 3).

Figure 3: System HiL at Robert Bosch Automotive Steering

In addition to the typical construction described above, the entire system under test is installed inside of a climate-controlled chamber capable of maintaining temperatures between -40°C and 120°C. There is also a possibility to test in a “driver closed loop” environment via a driver-seat mock-up with a real steering system and virtual vehicle. This mock-up can be installed in place of a steering robot, allowing a driver to “feel” steering behaviour during a simulation. In this way the System HiL is useful for evaluating simpler subjective phenomena in addition to system-level temperature effects.

4 Vehicle and Steering System Models

In this section, the development and validation of vehicle model systems and the steering system model shown in Figure 1 are described in more detail. The validation of the complete environment (steering and vehicle system) is described in Section 5.

4.1 Vehicle model

The basis of the virtual prototype used for the release (IPG CarMaker) are high fidelity vehicle models (Adams/Car) parameterized from component specifications and/or measurements. The positions, weights and component properties are hence modelled in the Adams/Car model. The conversion process to obtain a Carmaker model is divided in different sections for each subsystem of the vehicle.

The body is defined to have the same weight, center of gravity, inertia, chassis weights and position of rotating/translating parts.

The suspension properties are parameterized according to the Adams/Car model whereas the kinematics and compliance (K&C) are defined in look-up tables. In order to obtain the kinematics data, parallel and anti-parallel wheel motion is simulated in Adams including the steering sweep from end to end lock. The compliance requires force and torque load on wheel simulations simultaneously with parallel wheel travel. Additionally the K&C look-up tables may be based on measurement data (if available) to increase model fidelity. The standard steering system model from CarMaker is replaced with a specific model described below, combined with a steering wheel and column model specific for this project.

The tires models are the standard Magic Formula (MF) tire models parameterized from flat-track measurements based on the TYDEX standard tire interface and data format. In addition to the standard MF-Tire model [6] in CarMaker (version 5.1 and 6.1), the 3rd party MF-Swift tire model [7] with additional low-speed parking features was evaluated.

Finally, the powertrain is replaced with vehicle specific model supplied from the powertrain department and the aerodynamics are parameterized on data from either CFD simulations or wind tunnel measurements.

4.1.1 Sub-system Validation Methods

A validation of the kinematics and compliance is presented in Figure 4 showing of the lateral wheel centre displacement and the longitudinal toe-in compliance of the vehicle model compared to the Adams/Car model and measurements in a K&C rig.

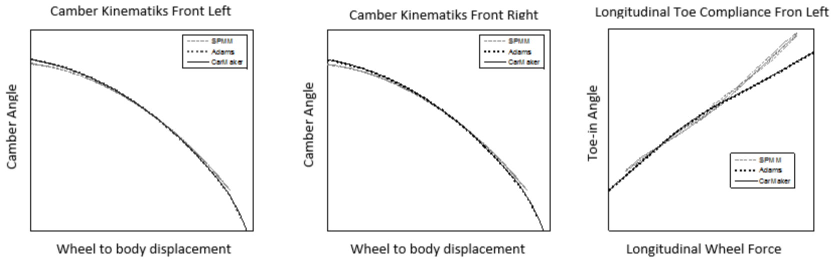


Figure 4: Lateral wheel centre displacement & longitudinal toe-in compliance.

Due to the varying fidelity requirements across the vehicle dynamics range, it is necessary to evaluate models with various complexities. Where conventional tire models have been showing potential in vehicle dynamics simulations above 10 km/h speeds, the need to simulate at lower speeds (ex: parking maneuvers) increase the model fidelity requirements. Figure 5 shows an example of steering wheel torque at standstill for various tire models compared to a real measurement.

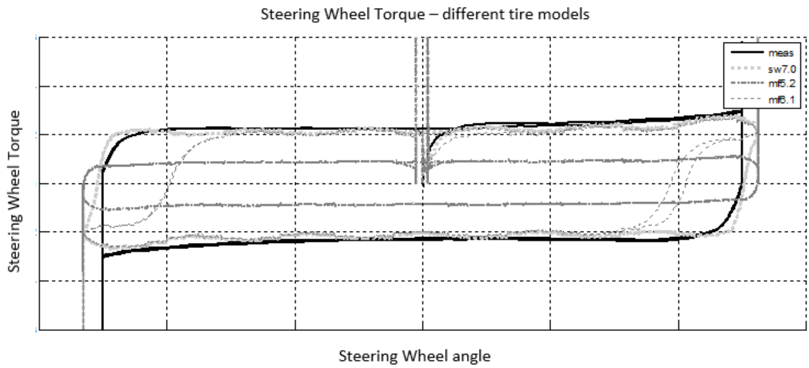


Figure 5: Steering wheel torque versus steering wheel angle of different tire models compared to measurement.

From Figure 5 it can be seen that the best correlation to measurement is obtained with the 3rd party tire model specifically designed to deal with the challenges of low-speed and stand-still tire force generation.

4.2 Steering model

For release activities where a steering model is preferable to a real steering system, a system model is used together with a software-in-the-loop (SiL) model of the software. In this application, a high importance is placed on model precision and validation.

4.2.1 Build

The model for the complete steering system can be separated into controller and plant model. The basis of the controller model is the complete steering system software in C code, compiled for Windows applications with a make-based process. By using the original software rather than a simplification, it can be guaranteed that as many software effects as possible are captured in the simulation.

There are, however, differences in implementation, hence hardware specific code sequences have to be replaced (e.g. direct memory access) and SiL-specific additional features like sensor hardware as well as vehicle bus emulation are necessary.

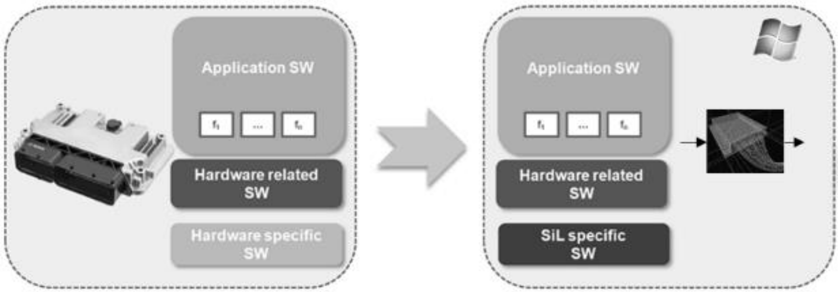


Figure 6: Visualization of SiL controller model build

The plant model covers effects of the mechanical and electrical parts of the steering system.

In addition to the model components, two different solvers are available for different applications: a simplified, real-time (1ms step) model and a complex model, able to capture all physical behaviour of the system, but with larger, variable step sizes.

4.2.2 Parameterization

Parameterisation of the SiL model is based upon the release parameters as defined by the software and application team. Access to these parameters at the controller model is similar to what is available in real prototypes (via the a2l file), and DCM tunings are transferable automatically.

Mechanical parameters such as inertia or geometries are derived from drawings, whereas functional characteristics such as friction or stiffness are derived from specific measurements performed with a nominal steering system on a test bench.

4.2.3 Validation

Before the steering system is integrated into the final vehicle simulation environment, a subsystem validation is performed. The first step in this process is the correlation of the controller model in order to confirm that the model has been built and parameterized correctly. Then a correlation of the complete steering model takes place, after which select fine tuning of the model parameters may be necessary to achieve an optimal correlation. Finally, a subset of maneuvers are used for rating the model quality in three frequency ranges: static response, command response (< 5 Hz), and reaction to disturbances (> 5 Hz). The model correlation quality across these frequency ranges can be seen below in Figure 7.

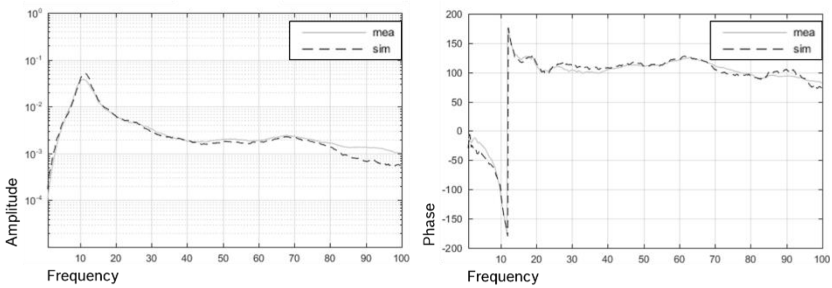


Figure 7: Transfer behaviour of SiL steering model (torsion bar torque – rack force)

5 Complete Simulation Environment Evaluation

Once the individual models have been validated and integrated into the complete simulation environment, the next step is to correlate the complete environment to a real vehicle to ensure that simulation results align closely with real-world maneuvers.

5.1 Data Collection

The following categories of ISO standards were used for the correlation: transient response (ISO 7401:2011), free steer (ISO 17288-1/2:2011), and on-centre handling (ISO 13674-1:2010).

In addition to the ISO maneuvers, a complete road release was logged to assess the model correlation using the supplier's own internal maneuvers and requirements.

Throughout these maneuvers it is essential to ensure not only that the vehicle dynamics (ex: lateral acceleration, roll angle, yaw rate, etc.) are recorded with an inertial measurement unit (IMU), but also that the interfaces to the steering system (ex: input shaft torque, rack force, etc.) and the internal steering system signals (ex: assist torque, rack position, etc.) are collected. An overview of these measured quantities is shown in Figure 8 below. This enables a much more thorough analysis at the steering system level.

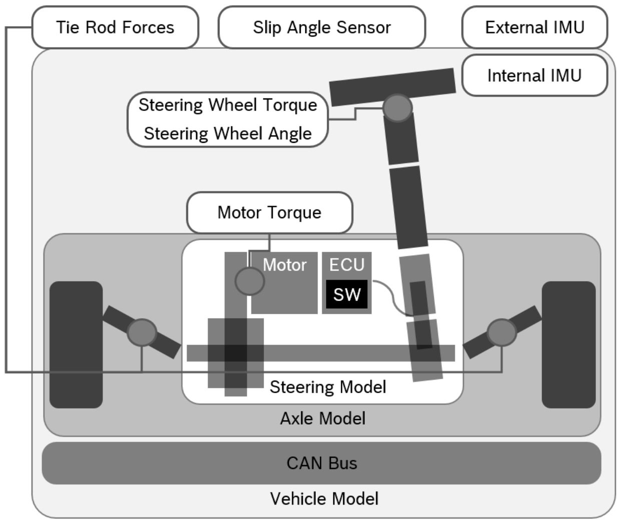


Figure 8: Diagram of select signal sources

5.2 Post Processing

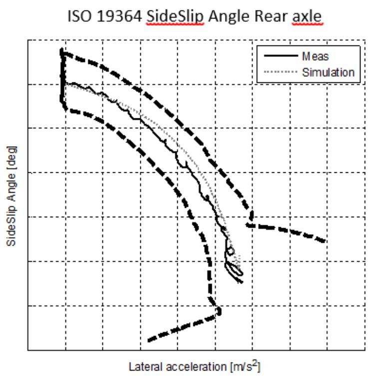
After collection, the data must be interpolated and post-processed at Bosch to align the simulation results to the real vehicle measurements. After this step, the correlation is performed with an automated evaluation script in Matlab to facilitate quick comparisons. Notable deviations are communicated openly and discussed in the team.

5.3 Results

Overall the simulation results with focus on the steering system compare favourably to reality. As anticipated, low speed maneuvers (under 10 km/h) and highly dynamic maneuvers (steering speeds greater than 600 deg/s) show some deviations. Two sets of maneuvers were selected for presentation that represent the present successes (ISO standards) and the challenges (parking).

5.3.1 ISO Validation Standards

To validate the simulation tool on a complete vehicle level, the procedure described in ISO 19364 and ISO 19365 are a valuable baseline. Figure 9 presents the body sideslip angle at rear axle versus lateral acceleration at constant radius with tolerance boundaries according to the standard. Figure 10 presents a sine with dwell time series with the last amplitude of steering wheel angle before stability controller intervention.



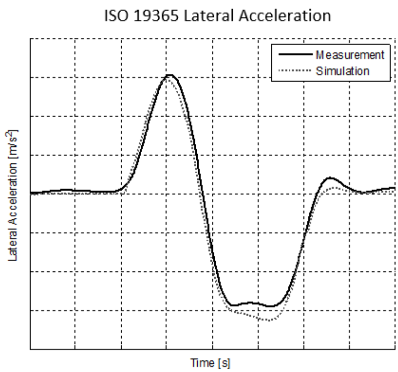


Figure 9: ISO 19364 Body sideslip angle at rear axle, validation with boundaries.

Figure 10: ISO 19365 Sine with Dwell on last steering wheel angle amplitude before stability control intervention.

Table 1 presents the metrics and tolerances stated in the ISO. The results are confirmed to be within the tolerances.

Table 1: ISO 19365 metrics validation.

ISO 19365 – Metric	Difference	Tolerance
First Peak	Pass	±15%
Second Peak	Pass	±20%
Time of Zero Crossing	Pass	±0.1s

5.3.2 Parking

In order to validate the tire model for standstill maneuvers a set of parking maneuvers were designed. As the previous MF5.2 tire model does not include turn slip equations that are essential for correlation to reality these maneuvers have been used to validate the MF-Swift 7.0 tire model with enhanced modelling of standstill dynamics.

The maneuvers are performed with a constant steering wheel velocity at both standstill and at low vehicle speed, consisting of multiple cycles of lock-to-lock steering inputs.

6 Summary and Outlook

6.1 Summary

Using simulations and test rigs to replace full vehicle testing in the area of road release is an ambitious but necessary goal to achieve the new customer requirements and shortened lead times of the future. Through close collaboration between Volvo Cars and Robert Bosch Automotive Steering a first step has been taken in achieving this.

The focus up until now has been towards achieving a satisfactory correlation between physical and virtual prototypes by using well-known ISO standard maneuvers. Parking is also being evaluated but since there is no ISO standard for parking custom maneuvers were defined.

Since the steering gear is the focus of the release, the important signals relate to the steering gear's interface to the vehicle. Those interface points are the input shaft and the tie-rod ends and that is where the external forces and torques need to be close enough to reality, as specified by requirements from the supplier.

Adequate correlation was achieved for all quasi static maneuvers, i.e. steady state and on center steering. The challenge remains highly dynamic maneuvers (ex: frequency response), particularly those with inputs greater than 3 Hz. Parking maneuvers are also a challenge due to tire model restrictions but solving this is ongoing, one possible solution being the implementation of MF-Swift 7.0 in the simulation environment.

6.2 Achieved goals

Apart from strengthening the collaboration between vehicle manufacturer and the system supplier, key to meeting the challenges in today's rapidly evolving automotive environment, the discussed methodology has achieved the following:

- Test coverage has been expanded. The amount of maneuvers that are performed during a road release has been expanded and is reproducible. This enables better control when performing regression analysis.
- The benefits of simulating multiple variants simultaneously have been proven. When it comes to the breadth of vehicle variants that can be included in the road release, improvements have been made. Since creating a new vehicle variant is a matter of exporting a MBS model, the limiting factor becomes the post-processing of the data for all simulated variants.
- Virtual methods has been tested in an ongoing vehicle project. Though physical prototypes were used in parallel while virtual testing was performed, continuously analyzing and improving the process is key to ensuring sustainable innovations.

6.3 Next steps

The next steps within the scope of this project are to extend the testing capabilities so that parking situations can be assessed and to continue to improve the correlation to reality.

Improving this correlation is continuous work – a better correlation leads to more test cases can be moved from a physical to a virtual prototype vehicle. In addition the analysis of further subjective acceptance criteria in further detail will be necessary. As such maintaining and improving the collaborative infrastructure developed through this project will be essential.

Moving forward these new capabilities will be put to use in the next great challenge of the automotive industry which is fully autonomous driving. The development and verification of these systems require the capabilities of repeatability and scalability, and the virtual methods developed and presented in this paper are key contributions to meet these challenges.

References

[1] P. Pfeffer and M. Harrer, Lenkungshandbuch, Springer Vieweg Verlag, 2013.

[2] P. Milbaier, “Evaluation of the Robustness of an EPS Control System in an Early Stage of the Product Development Life Cycle,” in *ATZ chassis.tech plus*, Munich, 2017.

[3] S. Grüner, “Objektive Bewertung von Lenkgefühl und Anwendung im Rahmen einer virtuellen Lenkgefühlsabstimmung,” in *ATZ chassis.tech plus*, Munich, 2017.

[4] G. J. Myers, The Art of Software Testing, John Wiley & Sons, 2004.

[5] “Safe Simulation at Volvo Cars,” *Agenda Magazine*, pp. 5-6, 3 2015.

[6] I. J. Besselink, A. J. Schmeitz and H. B. Pacejka, “An improved Magic Formula/Swift tyre model that can handle inflation pressure changes,” *Vehilce System Dynamics*, vol. 48, no. sup1: IAVSD Supplement, pp. 337-352, 2010.

[7] A. J. C. Schmeitz, I. J. M. Besselink and S. T. H. Jansen, “TNO MF-SWIFT,” *Vehicle System Dynamics*, vol. 45, no. sup1, pp. 121-137, 2007.